

An explanation for long flares from extragalactic globular cluster X-ray sources

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ABSTRACT

Repeatedly flaring X-ray binaries have recently been discovered in NGC 4697 by Sivakoff and collaborators. We show that these flares can be explained as the result of eccentric binaries in globular clusters which accrete more rapidly at periastron than during the rest of the binary orbit. We show that theoretical timescales for producing eccentricities and circularising the binaries are consistent with what is needed to produce the observed population of flaring sources, although the circularisation timescales are highly uncertain on both observational and theoretical grounds. This model makes two clear theoretical predictions (1) the flares should be seen to be strictly periodic if adequate sampling is provided, and that periodicity should be of approximately 15 hours (2) this class of flaring behaviour should be seen only in globular cluster sources, and predominantly in the densest globular clusters. We also test the model for producing eccentricities through fly-by’s of a third star near the binary in a globular cluster against a much larger database of millisecond pulsar observations than has been used in past work, and find that the theoretical cross sections for producing eccentricity in binaries are in reasonable agreement with most of the data, provided that the pulsar ages are about 4×10^9 years.

Key words: stellar dynamics – binaries:close – galaxies:star clusters – X-rays:binaries

1 INTRODUCTION

Extragalactic globular clusters span a much wider range of age and metallicity than do Galactic globular clusters. They also contain many more globular clusters; M 87, for example, contains about 10,000 globular clusters – two orders of magnitude more than the Milky Way does. As a result, rare events in globular clusters may be observable in other galaxies, but not in our own. At the present time, extragalactic globular clusters are too dense for the individual stars to be resolved, complicating searches for unusual stars that might be the results of interactions in these dense environments. It is likely though, that most globular clusters contain at most one bright X-ray binary, and these X-ray binaries can be observed to distances of tens of Megaparsecs. We could thus have some hope of finding signatures of unusual properties of the X-ray binaries that manifest themselves in the X-rays.

Identifying unusual X-ray binaries in globular clusters is more easily done in elliptical galaxies in particular than in our own Galaxy. This is partly because the metal rich globular clusters found more prevalently in elliptical galaxies than in spirals. Metal rich clusters are about three times as likely to contain an X-ray binary as metal poor clusters (Kundu, Maccarone & Zepf 2002), and this may contribute to the fact that ellipticals typically have 4% of their globular clusters with bright X-ray sources, while for spiral galaxies, this number is typically about 1-3% (Maccarone, Kundu & Zepf 2003).

In this paper, we show that recently discovered flaring X-ray binaries in NGC 4697 (Sivakoff, Sarazin & Jordan 2005 – SSJ05) may be presenting evidence of eccentric X-ray binaries in these globular clusters. We show that the observational data are consistent with the expectations for such eccentric binaries, and that it is reasonable for a few percent of the X-ray binaries to be eccentric enough for their accretion rates to be affected at periastron passage. We conclude that it is likely that such sources have not been found in the Milky Way because of small number statistics, and note that an eccentric binary model for a class of flaring behaviour makes two clear predictions: (1) that the flaring should be strictly periodic and (2) that the flaring sources in this class should be seen only in globular clusters, and preferentially in the densest globular clusters.

2 THE OBSERVATIONAL DATA

We briefly summarise the results of SSJ05. In that paper, they found evidence for strong flaring from three X-ray binaries in NGC 4697. The sample contained 157 X-ray sources, about 90% of which should be X-ray binaries, so $\sim 2\%$ of the X-ray binaries showed this strong flaring

behaviour. In two of the systems, the flaring had similar characteristics: frequent (i.e. roughly once per 10-15 hours) flares with durations of about 1000 seconds, luminosities of about 5×10^{38} ergs/sec (0.5-10 keV) and total flare energies of about 5×10^{41} ergs. The estimate of the frequency of the flares in these sources is quite rough, due to the relatively small number of observations and the sparse sampling of the data. SSJ05 note that the two most closely spaced flares in a single source occurred 11 days apart, and that there could be an additional population of sources which flare much more rarely, and whose flares simply did not occur within the observation windows. Thus, while the data are consistent with the idea that only a small number of sources flare, and that they flare with a frequency of about once per 15 hours, this is not a unique interpretation of the data. The third flaring system showed much shorter (duration of about 1 minute), much brighter flares (luminosities of about 5×10^{39} ergs/sec). The third flare was suggested by SSJ05 to be flaring activity from a “microblazar,” an X-ray binary whose jet is pointed at the observer (see e.g. Mirabel & Rodriguez 1999; K rding, Falcke & Markoff 2002).

3 WHY SUPERBURSTS CANNOT EXPLAIN THE DATA

The only possible explanation put forth by SSJ05 was that the two longer flares were superbursts. It was their intention that the reader would infer that they had dismissed the possibility (G. Sivakoff & C. Sarazin, private communications) due to the observational differences with Galactic superbursters discussed in their paper. We repeat here their discussion of what are the phenomenological differences between superbursts and the flares seen in NGC 4697, and place these differences in their theoretical context in order to make it more clear to readers not versed in burst theory that the observed differences are truly fundamental ones, and not differences that could be accounted for by tweaking parameter values such as accretion rate or the chemical composition of the accreted material.

Type I X-ray bursts as a broad class are generally explained as the runaway nuclear burning of piled-up accreted material in a layer on the surface of the accreting neutron star (for a review, see Lewin et al. 1993). The luminosities of these bursts are found to be at the Eddington limit or slightly below (Kuulkers et al. 2003). The decay timescale distribution of Type I X-ray bursts shows a bimodal distribution, with peaks at about 5 and 15 seconds (Kuulkers 2004).

Superbursts are a special class of Type I X-ray bursts, with much longer durations, typically about 3000–10000 seconds. Despite superbursts’ producing many more photons than classical Type I X-ray bursts, they were discovered decades after the first Type I X-ray bursts (Cornelisse et al. 2000), highlighting their rarity. It is generally believed that the same basic mechanism (i.e. runaway nuclear burning) is taking place in superbursts as in normal Type I X-ray bursts, but that instead of the bursts being powered by runaway thermonuclear burning of hydrogen and helium, they are believed to be powered by burning of carbon (Cumming & Bildsten 2001), or perhaps by a more complicated mechanism in which hydrogen atoms capture electrons to become neutrons, and then neutron capture by heavier atoms deeper in the atmosphere of the neutron star occurs (Kuulkers et al. 2002).

In only one case was a superburst found to have a peak luminosity in excess of the Eddington limit for solar composition material onto a $1.4 M_{\odot}$ neutron star, that of the superburst from 4U 1820-30 (Strohmayer & Brown 2002). It should be noted though, that in this case, the bursting system is known to be an ultracompact X-ray binary, where the accreted material is predominantly helium, and where the effective Eddington limit will thus be about twice as large as for accretion of hydrogen. There is thus no evidence for superbursts’ peak luminosities being more than about 10% above the Eddington limit. Additionally, since Type I bursts are generally thought to be spherical in nature (i.e. nuclear burning over the whole surface of the neutron star), it is expected that the Eddington limit should hold for these events, even if it might be possible to exceed the Eddington limit in the case of non-spherical accretion.

Several authors have also attempted to estimate the recurrence timescale of superbursts, based on both observational and theoretical grounds. Observationally, the recurrence timescale appears to be about one to two years (Wijnands 2001; Kuulkers 2002; in ’t Zand et al. 2003). Theoretical models predict similar (Cumming 2003) or somewhat longer values (Strohmayer & Brown 2002). For superbursts to be seen from the same source as frequently as the flaring sources discovered by SSJ05 would thus be indicating new nuclear physics, and not just a new range of parameter space being filled by accreting sources. For a more detailed review of the properties of superbursts, we refer the reader to Kuulkers (2004).

The properties of the Galactic superbursts thus present a few clear differences relative to the properties of the flaring events seen by SSJ05. The most important is the recurrence time difference. The two sources suggested by SSJ05 to be candidate superbursters each showed a flare in 3 of the 5 observations of NGC 4697, which had durations of about 40 kiloseconds each. This gives a flare rate of about one per 70000 seconds, or about 1000 times as often as the Galactic superbursts appear to occur. As the superburst recurrence timescale is set largely by nuclear physics, it is highly unlikely that simply tweaking parameter values could increase the superburst rates to the levels seen in the NGC 4697 sources.

The luminosities of four of the six events claimed to be superbursts are above the Eddington limit even for a helium-accreting neutron star, and the event durations of 5 out of the six candidates are less than 2000 seconds. Furthermore, the conversion from count rate to luminosity was done using a $\Gamma = 1.4$ power law, which yields a luminosity about 2.7 times lower than a more realistic spectral model for a superburst (SSJ05). This means that most of the flares are at least a factor of 5 times brighter than any known Galactic superburst, further weakening the cases that these events are truly superbursts. While the measured event durations are also inconsistent with the observations of Galactic superbursts, this quantity is highly susceptible to measurement error for the extragalactic flares, since there are relatively few photons from which to estimate the light curve shape of the burst.

4 ECCENTRIC BINARIES

An alternative way to produce multiple bright flares in a single X-ray binary is to have a frequently occurring type of event that boosts the actual accretion rate. The most natural such type of event would be a periastron passage in an eccentric binary. One can consider the case of

the Galactic X-ray binary Circinus X-1 as an example of such a system. This object has a 16.6 day orbital period, with strong flares in the X-rays seen at each periastron passage (e.g. Kaluzienski et al. 1976; Clarkson, Charles & Onyett 2004).

On the other hand, the eccentricity of Cir X-1 is quite large, with estimates in the 0.80-0.95 range (e.g. Tauris et al. 1999). There are no other low mass X-ray binaries with known eccentricities, so there is no clear empirical evidence about what to expect for the effects on the accretion rate of an eccentric low mass X-ray binary with small, but non-zero, eccentricity. However, theoretical predictions have been made. Hut & Paczynski (1984) considered the cases of isothermal flows and polytropic flows and found that:

$$\frac{\partial \ln \dot{M}}{\partial \ln(R_2/R_{L2})} \approx 2 \times 10^4, \quad (1)$$

where \dot{M} is the mass accretion rate, R_2 is the radius of the mass donor star, and R_{L2} is the distance from the center of the mass donor star to the second Lagrangian point (i.e. the size of the Roche lobe of the mass donor). Slightly larger values are found for isothermal flows, and slightly smaller values for polytropic flows. Therefore, if one changes the eccentricity from zero to 0.001 while leaving the semi-major axis unchanged, that is enough to increase the mass transfer rate by a factor of 100 (Hut & Paczynski 1984).

The next question is whether it is feasible for the changes in the mass accretion rate to manifest themselves as periodic behaviour. The relevant timescale is then the viscous timescale from the outer part of the accretion disk. The viscous timescale, t_{visc} , can be defined in terms of the dynamical timescale, t_{dyn} , such that:

$$t_{visc} = (H/R)^{-2} \alpha^{-1} t_{dyn}, \quad (2)$$

where H is the scale height of the disk, R is the radius of the location in the disk where the viscous timescale is being computed, and α is the dimensionless viscosity parameter. Since the accretion rates we are considering are quite high, the accretion is likely to proceed through a geometrically thick accretion disk, with $H/R \sim 1$, and α likely to be relatively large for large accretion rates (Blaes 1987; Abramowicz et al. 1988). The circularisation radius is typically about 1/7 of the orbital separation, yielding a dynamical timescale at the circularisation radius of about 1/20 of the orbital period. A value of α of about 0.3 or more would then give timescales for the flare events that are consistent with the measurements of SSJ05, assuming that the orbital periods of the binaries are about 15 hours – a bit longer than the observations used to find the flare – as would be expected by the finding that the flaring sources each showed flares in 3 of the 5 observations.

That the two flaring sources are seen in globular clusters bolsters the idea that they might be eccentric. Globular cluster X-ray binaries are generally thought to be produced through dynamical interactions of some kind – tidal captures (Clark 1975; Fabian, Pringle & Rees 1975) or three-body or four-body exchange interactions (e.g. Hills 1976; Fregeau et al. 2004). These interactions are likely to leave behind highly eccentric binaries, or in some cases, even to leave behind products of stellar collisions. Another possibility that is less often discussed is that accretion takes place in systems hardened by interactions with other stars or binaries (Krolik, Meiskin & Joss 1984). These interactions will also perturb the binary orbits so that the binaries become eccentric (Hut & Paczynski 1984; Rappaport, Putney & Verbunt 1989; Phinney 1992; Rasio & Heggie 1995; Heggie & Rasio 1996).

5 RATE OF PERTURBATIONS TO THE ECCENTRICITY

Two cases exist for producing eccentric X-ray binaries – first that the eccentricity is induced in the encounter forming the X-ray binary, and secondly that the eccentricity is induced after formation. Recent numerical simulations do indicate that a large fraction of 3-body and 4-body interactions produce eccentricities well in excess of 0.1 (Fregeau et al. 2004). Many products of tidal capture (Di Stefano & Rappaport 1990) are also expected to be highly eccentric. It is not clear how stable such systems are; they probably undergo thermal timescale mass transfer and have very short lives as X-ray sources (Hut & Paczynski 1984). In the interests of making conservative estimates of how many eccentric X-ray binaries there should be, we will focus on the case where an initially circular binary has an eccentricity induced by a third star passing near to it. This most likely corresponds to the real formation scenario of an eccentric, but non-contact binary being formed by a stellar interaction, circularising, and then coming into contact due to gravitational radiation and stellar evolutionary effects.

We thus wish to find whether the duty cycle as an eccentric source is large enough to account for the observed fraction of the objects showing bright flares. Let us consider the case where the eccentricity enhances the mass transfer rate by a factor of about 10 (since the flares observed by SSJ05 are at a count rate of about 10 times the non-flaring level). This requires an eccentricity of about 0.0001, though the exact value depends on whether the star is better treated as a polytrope or as an isothermal flow at the inner Lagrangian point (Hut & Paczynski 1984).

We can estimate the probability that a given eccentricity will be induced in an X-ray binary by using cross-sections for eccentricity tabulated by various authors. The most recent work on this topic is that of Heggie & Rasio (1996). For the case where small eccentricities are generated, they find that:

$$\sigma(\delta e > \delta e_0) = 4.62 \left(\frac{m_3 |m_1 - m_2|}{M_{12}^2} \right)^{2/5} \left(\frac{M_{12}}{M_{123}} \right)^{1/5} \frac{GM_{123}a}{V^2} \delta e_0^{-2/5}, \quad (3)$$

where $\sigma(\delta e > \delta e_0)$ is the cross-section for producing an eccentricity increases greater than δe_0 , m_1 is the accretor's mass, m_2 is the donor star's mass, m_3 is the mass of the third body passing nearby the binary, M_{12} is the total mass of the binary system, M_{123} is the sum of the masses of all three stars, G is the gravitational constant, a is the semi-major axis of the binary system, and V is the relative velocity of the centre of mass of the binary and the third star.

We then follow the work of Hut & Paczynski (1984), and compute the timescale for an interaction to occur, assuming the velocity distribution of the stars follows is Maxwellian. Hut & Paczynski (1984) did point out correctly both that the lowered Maxwellian using in

King models would be a better approximation to the real velocity distributions of globular clusters, and that the difference between the two distributions is small except in the very high velocity tail, which contributes at a very small level to the cross section anyways. Since it will be straightforward to compute an analytic expression for the interaction timescale only from the Maxwellian distribution, we therefore use the Maxwellian.

The timescale, τ , for an interaction for a single binary is then given by:

$$1/\tau = n < \sigma V > = n \left(\frac{2}{\pi} \right)^{1/2} \left(\frac{\mu}{kT} \right)^{3/2} \int_0^\infty \exp(-\mu v^2 / 2kT) \sigma(V) V^3 dV, \quad (4)$$

where n is the density of stars, k is the Boltzmann constant, $\mu = \frac{m_3(m_1+m_2)}{m_1+m_2+m_3}$ is the reduced mass of the three star system, and $v_{th} = (3kT/M_\odot)^{1/2}$ defines the temperature T , in terms of the thermal velocity v_{th} , which is approximately the same as the velocity dispersion, as in the case of the Maxwellian distribution, the globular cluster is approximated as a gas of particles with masses of a solar mass and temperature T . We then re-write this expression, in terms of the velocity dispersion, σ_v , rather than the “temperature,” in order to express the results in terms of observables:

$$1/\tau = n < \sigma V > = n \left(\frac{2}{\pi} \right)^{1/2} \left(\frac{3\mu}{M_\odot \sigma_v^2} \right)^{3/2} \int_0^\infty \exp[-3\mu v^2 / (2M_\odot \sigma_v^2)] \sigma(V) V^3 dV, \quad (5)$$

Substituting the expression for the cross-section from Equation 3, we find:

$$\tau = 7 \times 10^{10} \text{ yr} \left(\frac{a}{0.01 \text{ AU}} \right)^{-1} \left(\frac{n}{10^5 \text{ pc}} \right)^{-1} \left(\frac{\sigma_v}{10 \text{ km/sec}} \right) \left(\frac{m_3 |m_1 - m_2|}{M_{12}^2} \right)^{-2/5} \left(\frac{M_{12}}{M_{123}} \right)^{-1/5} \left(\frac{\mu}{m_\odot} \right)^{-1/2} \left(\frac{M_{123}}{M_\odot} \right)^{-1} e^{2/5} \quad (6)$$

This gives a timescale to produce the eccentricity of 0.0001 of about 10^9 years for parameter values of $m_1 = 1.4 M_\odot$, $m_2 = m_3 = 1.0 M_\odot$, $n = 5 \times 10^5$, $\sigma_v = 10 \text{ km/sec}$, and $P = 10 \text{ hrs}$, typical values in a dense globular cluster. We note that this formula breaks down for very close approaches, which can then yield very large eccentricities. For such close approaches, the cross-section scales with the logarithm of the final eccentricity, rather than as a power law function of the final eccentricity. Such cases will not be relevant for the low mass X-ray binaries we study here.

We can also test the theoretical predictions of the timescale for producing eccentricity by comparing with the millisecond pulsar population of the Galaxy’s globular clusters. This was previously done with inconclusive results by Rasio & Heggie (1995), but that was with only nine binary pulsars. There are now 31 known binary pulsars with good orbital data compiled in Camilo & Rasio (2005). For these systems, we can find the expected e given different assumptions about the pulsar lifetime, and then plot the expected versus observed values. A few caveats will apply. First, for pulsars which do not have positions measured accurately, we will assume that the local stellar density and velocity dispersion are the core density and core velocity dispersion for the cluster, which will usually, but not always, be a good approximation. We will use a separate symbol to identify these pulsars. Secondly, we will compute the expected eccentricity only in the power law regime, so the expected eccentricities of the widest binaries will be underestimates.

We take the estimates of the globular cluster velocity dispersion from Gnedin et al. (2002). We assume the perturbing star will have a mass of $1 M_\odot$, and that the timescale for inducing a perturbation is 4 Gyr. We also assume no stellar or orbital evolution over that 4 Gyr. The central densities are taken from the Harris catalog (Harris 1996). The results are plotted in Figure 1. Given typical pulsar ages of about 4 Gyr, there seems to be a reasonable agreement between model and data in the sense that the median data values are close to the theoretically predicted trend. On the other hand, there is considerable scatter about this median. Furthermore, the 4 Gyrs typical age is in line with what is expected from models that attempt to explain the relative number densities of LMXBs and millisecond pulsars seen in globular clusters today (e.g. Davies & Hansen 1998).

The reasons for the scatter are likely to be many. Some spread in binary pulsar ages is likely; not all these pulsars are in the cores of their host clusters; the effects of four-body interactions are not considered by Heggie & Rasio (1996); and some of the pulsars might be in the tail of the space velocity distribution, especially if they were formed in exchange interactions.

We note that there is a poor agreement for observed eccentricities above about 0.01, but that this is likely to be due primarily to the fact that this is the regime for which the power law relation between eccentricity and waiting time changes into a logarithmic relationship. Another clear outlier is the highly eccentric pulsar, M 15C, which is also 13 core radii from the centre of the cluster, and is thought to have been involved in a recent exchange interaction (Phinney & Sigurdsson 1991). The cross-section for that interaction should have been determined by an orbital period much longer than the current period, and hence that the cross-section for the interaction which produced the eccentric orbit may have been much larger than the cross-section for the perturbation of its current orbit. In fact, its predicted eccentricity is well below the range plotted here, while its actual eccentricity is about 0.68, clearly indicating that some mechanism other than “gentle” fly-by encounters produced its eccentricity. Another system, NGC 6752A and its low eccentricity combined with its location so far out in the cluster have been used to suggest that the system experienced a recoil from a black hole-black hole binary in the core of NGC 6752 (Colpi, Possenti & Gualandris 2002), again indicating that not all binary pulsars eccentricities will be well described by the framework of gentle fly-by induced eccentricities. Still, though, as the bulk of the measurements and the upper limits agree reasonably well with a $\sim 4 \times 10^9$ year pulsar lifetime and the basic model for inducing eccentricities of Rasio & Heggie (1995), it seems reasonable to use this approach as a guide to estimating the number of moderately eccentric binaries there will be in a globular cluster.

5.1 The circularisation timescale

The observational and theoretical status of the circularisation of binaries containing giant donors is well established. It is generally found that the circularisation timescales of such systems is of order 10000 years (Zahn 1977; Verbunt & Phinney 1995), with theory in good

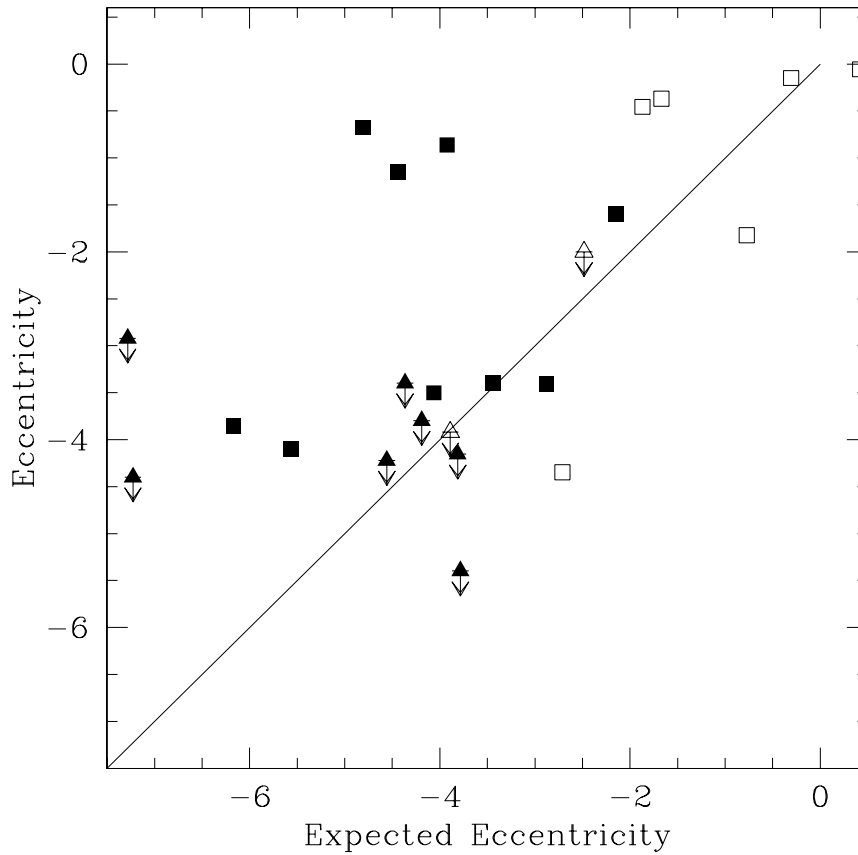


Figure 1. The expected versus observed eccentricities for the globular cluster pulsars tabulated by Camilo & Rasio (2005). Squares represent observed eccentricity values, while triangles represent upper limits. The calculations assume a lifetime of the pulsar system of 4×10^9 years, during which there has been no orbital evolution except due to interactions with a third body. The line shows where the expected and observed eccentricities are equal, and is plotted to guide the eye. Filled symbols indicate pulsars whose positions are well known, while open symbols indicate pulsars whose positions are not well measured and which are hence assumed to be in their cluster cores.

agreement with the data. The circularisation rate of short period eccentric binaries containing low mass main sequence stars is not currently well understood observationally or theoretically. Observations of open clusters have done much to test theory for the circularisation rates of longer period binaries, but it seems that binaries with periods shorter than about 8 days are circularised during their pre-main sequence phases of stellar evolution (Mathieu et al. 1992). As a result, if a shorter period binary forms after the star has ended its pre-main sequence phase of evolution, there is not a straightforward way to use observations of the tidal circularisation cutoff periods of open clusters in order to estimate the circularisation rate for such binaries.

We must, then rely on some combination of theoretical work and extrapolation of the observational data. The key question is thus whether it is plausible for a few percent of the X-ray binaries to have eccentricities greater than about 0.0001. This essentially boils down to the question of whether the tidal circularisation timescale can be about 0.01 times the timescale on which perturbations produce an eccentricity of about 0.0001. In fact, a lower fraction could still be consistent with the data, since the eccentric binaries have their accretion rates boosted due to the eccentricity, and hence the observable (i.e. flux-limited) sample of X-ray binaries should be biased towards eccentric binaries.

The theory and observational understanding of circularisation of eccentric binaries with low mass main sequence stars is still in its early stages, due to uncertainties regarding convection and turbulence within stars. If one takes the most optimistic case in the theoretical literature, that of Goodman & Dickson (1998) in the case of inefficient linear damping of tidally excited g -modes, one finds that the circularisation timescale is about $150 P_d^3$ Myrs, which would be about 20 Myrs for the 0.5 day periods being discussed here, and would give a few percent of the X-ray binaries in sufficiently eccentric orbits to allow observable effects. If one takes a more conservative case, such as that of Witte & Savonije (2002), then one can extrapolate their published relation to estimate a circularisation timescale of a few Myrs for periods of about 0.5 days, still marginally consistent with the data. Furthermore, the results of Witte & Savonije (2002) invoke resonant effects to speed up the circularisation process. These resonant effects are not likely to be important for eccentricities below about 0.1, so the removal of the last bit of eccentricity from a nearly circular binary would be expected to happen on a slower timescale than a few Myrs. On the other hand, other groups, such as Terquem et al. (1998) and Claret & Cunha (1997) have suggested much more rapid circularisation of short period binaries, with a stronger dependence of circularisation timescale on binary period, and furthermore, the circularisation process may be accelerated due to mass transfer in contact binaries.

The biggest problem most of the theoretical work has in matching the observations is to explain the presence of the longest period circular binaries; that is to say, most of the theoretical work seems to underestimate the circularisation rate for one reason or another. As a result, it is probably safest to assume circularisation rates higher than those typically proposed in the literature, at least for the longer period binaries. This still yields few constraints for the circularisation timescales of the lower period binaries, since the dependence of the circularisation timescale on period is not well constrained. At the present time, observations are ongoing to measure circularisation periods in more open clusters (e.g. Meibom & Mathieu 2005), but if the supposition that much of the circularisation of normal binary stars occurs on the pre-main sequence is correct, then such observational work will never address the question of circularisation of short period binaries. In fact, the globular cluster X-ray binaries (along with other similar systems such as binary pulsars in globular clusters) might then present the best test ground for this work. A large sample of flaring X-ray sources associated with eccentric orbits through proof that the flares were periodic could provide a key data set of great use in refining models of tidal circularisation of short period binaries containing solar-type stars.

5.2 Observational tests

The most obvious observational test of this model is that the flares should be periodic, on the binary period. Based on the fact that the flares in the NGC 4697 sources were seen in multiple observations, we infer that the orbital periods, at least of these sources, cannot be much larger than the observation durations, which were about 11 hours. The lack of multiple flares being seen in a single observation would suggest that the periods are at least a bit longer than 11 hours, although it was noted by Sivakoff et al. (2005) that the method of detecting these flares relied on comparing the count rate in a given window to the average count rate observed from the source, which led to a bias against sources which show multiple flares. Use of more sophisticated statistical methods for flare finding such as Bayesian blocks (Scargle 1998) might have greater sensitivity to shorter period eccentric systems, which could show multiple flares. Ideally, one would have continuous observations of at least 30 hours on a single galaxy which is at least as nearby as NGC 4697, or XMM observations, with their higher count rates, on a galaxy at roughly the same distance as NGC 4697.

Additionally, if larger samples of such flaring sources can be collected, such flaring sources should be found preferentially in dense globular clusters. While some systems such as Circinus X-1 are likely to exist, these should have short lifetimes after the supernova explosion forming them (i.e. they should have been eccentric only for a timescale of order the circularisation timescale). As a result, these should only exist in young stellar populations, even if they do have low mass donors. Therefore, elliptical galaxies should show such periodically flaring X-ray binaries only when eccentricities can be induced in the binary long after its formation. This should happen only in regions of high stellar density (i.e. globular clusters, and to be more specifically, predominantly in the densest regions of the densest clusters).

Additionally, we have some hope for finding evidence of these eccentric accreting binaries in our own Galaxy, and using their numbers to estimate how many such systems should exist in other galaxies. For example, the X-ray and optical properties of AC 211, the accretion disk corona source in M 15, might be explained as the result of the effects of binary eccentricity. Van Zyl et al. (2004) suggest that this system may have a rather large mass ratio, despite its long orbital period. This would imply a low mass transfer rate, at odds with the inferred high mass transfer rate. A large eccentricity would boost the mass transfer rate substantially. Obviously there are other ways to affect the mass transfer rate of this system, and eccentricity is not currently required by the data. A more effective way to test for eccentricity in this system would be to obtain a more detailed radial velocity curve than currently exists.

It would also be fruitful to look at the eccentricity distributions of the cataclysmic variable stars (CVs) in globular clusters in the Milky Way. As there are many more of these systems than millisecond pulsars, it should be easier to collect a large sample of objects. Unfortunately, at the present time, eccentricity measurements of globular cluster CVs have not been made. This is partly because only recently have high resolution ultraviolet surveys started to unveil the large populations of CVs in globular clusters (e.g. Knigge et al. 2002), and partly because accurate measurements of very small eccentricities are difficult to make except in pulsar systems. Searches for eccentric CVs should become feasible in the near future though, with adaptive optics spectroscopy, especially if CVs show emission lines in the infrared, such as Bracket γ . It might also be possible to determine whether some magnetic CVs are in eccentric orbits based on pulse timing. Intermediate polar systems show pulsation and orbital periods different from one another, and using the pulsar as a clock, one can make accurate measurements of the orbital parameters.

6 CONCLUSIONS

We have shown that the recent discovery of repeated flaring from two of the X-ray binaries in NGC 4697 may be indicative of the fact that these systems are in eccentric orbits. The sharp, frequent increases of the luminosity are consistent with the expectations for Roche lobe overflow from a star in an eccentric orbit around a compact object. The expected number of eccentric low mass X-ray binaries is consistent with the observed number of systems showing repeating flaring behaviour in NGC 4697. We have also discussed future tests for determining whether the assumptions about eccentricity evolution on which this work is based are correct.

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REFERENCES

- Abramowicz M.A., Czery B., Lasota J.P., Szuszkiewicz E., 1988, *ApJ*, 332, 646
- Blaes O.M., 1987, *MNRAS*, 227, 975
- Camilo F., Rasio F.A., 2005, *ASP Conf. Ser. Vol. 328: Binary Radio Pulsars*, eds. F. A. Rasio & I. H. Stairs (San Francisco: ASP), p. 147
- Claret A., Cunha N.C.S., 1997, *A&A*, 318, 187
- Clark G.W., 1975, *ApJ*, 199L, 143
- Clarkson W.I., Charles, P.A., Onyett, N. 2004, *MNRAS*, 348, 458
- Colpi M., Possenti A., Gualandris A., 2002, *ApJ*, 570, 85L
- Cornelisse R., Heise J., Kuulkers E., Verbunt F., in 't Zand J.J.M., 2000, *A&A*, 357, L21
- Cumming A., 2003, *ApJ*, 595, 1077
- Cumming A., Bildsten L., 2001, *ApJ*, 559, 127L
- Davies M.B., Hansen B.M.S., 1998, *MNRAS*, 301, 15
- Fabian A.C., Pringle J.E., Rees M.J., 1975, 172P, 15
- Fregeau J.M., Cheung P., Portegies Zwart S.F., Rasio F.A., 2004, *MNRAS*, 352, 1
- Gnedin O.Y., Zhao H.S., Pringle J.E., Fall S.M., Livio M., Meylan G., 2002, *ApJ*, 568, L23
- Goodman J., Dickson E.S., 1998, *ApJ*, 507, 938
- Harris W.E., 1996, *AJ*, 112, 1487
- Heggie D.C., Rasio F.A., 1996, *MNRAS*, 282, 1064
- Hills J.G., 1976, *MNRAS*, 175P, 1
- Hut P., Paczynski B., 1984, *ApJ*, 284, 685
- in 't Zand J.J.M., Kuulkers E., Verbunt F., Heise J., Cornelisse R., 2003, *A&A*, 411, 487L
- Kaluzienski L.J., Holt S.S., Boldt E.A., Serlemitsos P.J., 1976, *ApJ*, 208, L71
- Knigge C., Zurek D.R., Shara M.M., Long K.S., 2002, *ApJ*, 579, 752
- Körding E., Falcke H., Markoff S., 2002, *A&A*, 382L, 13
- Krolik J.H., Meiskin A., Joss P.C., 1984, *ApJ*, 282, 466
- Kundu A., Maccarone T.J., Zepf S.E., 2002, *ApJ*, 574 L5
- Kuulkers E., 2002, *A&A*, 383, L5
- Kuulkers E., den Hartog P.R., in 't Zand J.J.M., Verbunt F.W.M., Harris W.E., Cocchi M., 2003, *A&A*, 399, 663
- Kuulkers E., 2004, *Nuclear Physics B*, 132, 466
- Maccarone T.J., Kundu A., Zepf S.E., 2003, *ApJ*, 586, 814
- Mathieu R.D., Meibom S., Dolan C.J., 2004, *ApJ*, 602, 121L
- Mathieu R.D., Duquennoy A., Latham D.W., Mayor M., Mermilliod T., Mazeh J.C., 1992, *Binaries as Tracers of Stellar Formation. Proceedings of a Workshop held in Bettmeralp, Switzerland, Sept. 1991, in honor of Dr. Roger Griffin*. Editors, Antoine Duquennoy, Michel Mayor; Publisher, Cambridge University Press, Cambridge, England, New York, NY
- Meibom S., Mathieu R.D., 2005, *ApJ*, 620, 970
- Mirabel I.F., Rodriguez L.F., 1999, *ARA&A*, 37, 409
- Phinney E.S., 1992, *Phil. Trans. Roy. Soc. Lon.*, 341, 39
- Phinney E.S., Sigurdsson S., 1991, *Nature*, 349, 220
- Rappaport S., Putney A., Verbunt F., 1989, *ApJ*, 345, 210
- Rasio F.A., Heggie D.C., 1995, *ApJ*, 445L, 133
- Scargle J.D., 1998, *ApJ*, 504, 405
- Sivakoff G.R., Sarazin C.L., Jordan A., 2005, *ApJ*, 624L, 17
- Strohmayer T.E., Brown E.F., 2002, *ApJ*, 566, 1045
- Tauris T.M., Fender R.P., van den Heuvel E.P.J., Johnston H.M., Wu K., 1999, *MNRAS*, 310, 1165
- Terquem C., Papaloizou J.C.N., Nelson R.P., Lin, D.N.C., 1998, *ApJ*, 502, 788
- van Zyl L., Ioannou Z., Charles P.A., Naylor T., 2004, *A&A*, 428, 935
- Verbunt F., Phinney E.S., 1995, *A&A*, 296, 709
- Wijnands R., 2001, *ApJ*, 554, L59
- Witte M.G., Savonije G.J., 2002, *A&A*, 386, 222
- Zahn J-P., 1977, *A&A*, 57, 383